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Preface

This volume includes the articles presented at the “Xth International Conference of Production Research-Americas” (ICPR-Americas 2020), held virtually from Bahía Blanca, Argentina from December 9 to 11, 2020. This conference was organized by the local organizing committee of the city of Bahía Blanca and was sponsored by the *International Foundation of Production Research* (IFPR). This conference aims at exchanging experiences and encouraging collaborative work among researchers and practitioners from the Americas and the Caribbean region.

The first ICPR Americas conference, took place in November 2002 in Saint Louis, Missouri, USA under the general theme of “Production Research and Computational Intelligence for Designing and Operating Complex Global Production Systems”. This conference generated very positive responses from the attendees. From then on, the ICPR regional meeting was held at alternate years. The second version of the ICPR-Americas was held in August 2004 in Santiago, Chile with the conference theme “Information and Communication Technologies for Collaborative Operations Management”. The third edition of the ICPR-Americas held in Curitiba, Brazil, had the general theme of “Rethinking Operation Systems: New Roles of Technology, Strategy and Organization in the America’s Integration Era”. This instance sought to promote a deep discussion about the role of Production Engineering in the America’s integration process. In 2008, the venue of ICPR-Americas was Sao Paulo, Brazil at the Universidade de Sao Paulo Campus. The conference had the theme “The Role of Emerging Economies in the Future of Global Production: Creating New Multinationals”. Bogota, Colombia hosted in 2010 the fifth conference with the subject “Technologies in Logistics and Manufacturing for Small and Medium Enterprises”. The sixth edition (2012) was organized around the topic “Production Research in Americas Region: Agenda for the Next Decade” by the University of Santiago de Chile in Santiago. In Lima, Peru, the 2014 edition of ICPR-Americas addressed the general theme of “Towards Sustainable Eco-Industrialization through Applied Knowledge.”. The eighth edition was held at Valparaíso, Chile in 2016, and more recently, in 2018, the ninth conference was held at Bogotá, Colombia under the topic „Improving Supply Chain Management through Sustainability“

ICPR-Americas 2020 was the first edition carried out in virtual mode, due to the COVID-19 pandemic. Thanks to the participation and commitment of the attendees, the conference was carried out successfully, allowing many young researchers to participate in an international conference, in a year in which these opportunities were scarce. The ICPR-Americas meeting space gave them the opportunity to share their work, as well as exchange ideas and points of view, all in the cordial atmosphere that characterizes the ICPR-Americas conferences.

ICPR-Americas 2020 was organized by a local committee of the National University of the South, supported by the university and IFPR.

The conference received more than 280 papers, of which 245 were accepted and presented during the conference. The nationality of the authors was representative of the vast

majority of the countries of America, not only South America, but also Central and North America. Something that enriched the international experience that each of the participants took from the conference.

A couple of events associated with ICPR-Americas 2020 were also held: the “SIMPOSIO INDUSTRIAL” and the “SEMINARIO de ENSAYOS ESTUDIANTILES”. Both events allowed to broaden the scope and attendance of the conference. The accepted and presented works of both events are compiled within this volume.

Finally, it only remains for us to thank the National University of the South, especially the Departments of Engineering and Mathematics, as well as the General Secretariat of Science and Technology, for the support provided to carry out the event.

March 2021

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ÍNDICE

PLENARY DISSERTATIONS

Manufacturing Scheduling: Old solutions for new problems? Jose M Framinan. **P. 28**

Perspectives and trends of Industry 4.0 in Latin America. Gonzalo Mejía Delgadillo. **P. 30**

Digitalization of manual production and assembly processes for smart factories of the future. Francesco Pilati. **P. 31**

Managing Macro Level Supply Chain Disruptions: Lessons from COVID-19. Srinivas Talluri. **P. 33**

GENERAL SESSION

Advanced Energy Management: a review on Energy Management and I4.0. Caio Cesar Ferreira, Sergio E. Gouvea da Costa, Edson Pinheiro de Lima and Fernando Deschamps. **P. 36**

A simulation-optimization approach for the household energy planning problem considering uncertainty in users preferences. Diego Gabriel Rossit, Sergio Nesmachnow, Jamal Toutouh and Francisco Luna. **P. 40**

Seleção de um Sistema de Gerenciamento de Transportes numa Empresa do Setor Educacional. Goreth de Carvalho Gonçalves, Claudemir Leif Tamarico and Fernando Augusto Silva Marins. **P. 55**

Desarrollo de un modelo matemático para el problema de enrutamiento e inventario con múltiples depósitos (MDIRP). Javier Arias-Osorio and Erick Saenz Hoyos. **P. 70**

Estimating the Dynamic Impact of COVID-19 State-level Mobility Interventions in Brazil. Thyago C. C. Nepomuceno, Marcele Elisa Fontana and Thaltes Vitelli Garcez. **P. 80**

Desenvolvimento de produto Lean e Green: um estudo comparativo entre PMEs Brasileiras e Japonesas. Gisele Piovesan, Gilson Oliveira, Shoji Takechi, Kim Tan and Dalmarino Setti. **P. 93**

Multi-objective optimization of a rotary dryer in a semi-dynamic state using evolutionary algorithms. Benjamín Barán, César Oviedo and Michel Galeano. **P. 108**

Modelado mecánico de procesos de molienda de maíz: Calibración de parámetros para el modelado por elementos discretos (DEM). Manuela Quezada Henry, Alejandro Chiaravalle, Juliana Piña and Ivana Cotabarren. **P. 121**

The time-lagged effect problem on (un)truthful data, a case study on COVID-19 outbreak. Luis Rojo-González. **P. 136**

Nuclear Safety Management after Fukushima accident. A systematic and critical review of the state of the art. Gregorio Acuña, Marcelo Gimenez and Marisa Sanchez. **P. 150**

Planejamento de Vendas e Operações e Planejamento Integrado de Negócios em um Banco Privado do Brasil. Jefferson Barbosa Araujo, Claudemir Leif Tamarico and Fernando Augusto Silva Marins. **P. 165**

Application of the AHP method to assist the strategy of bike share station positioning in the city of São Paulo. Emannuell Cenzi, José João Manrique Franco, Marcelo Rudek and Eduardo de Freitas Rocha Loures. **P. 179**

Hacia el desarrollo de una movilidad inteligente para la ciudad de Bahía Blanca: Primer enfoque sobre la caracterización de la flota vehicular del microcentro. Yamila Soledad Grassi, Nélida Beatriz Brignole and Mónica Fátima Díaz. **P. 189**

Inventario de Emisiones de la Aviación Civil, Navegación Marítima y Ferrocarriles de la ciudad de Bahía Blanca para el año 2018. Yamila Soledad Grassi, Nélica Beatriz Brignole and Mónica Díaz. **P. 204**

Minimizing the Bullwhip Effect by Forecasting Supply Chain Demand: Case Study of the Argentine Automotive Sector. Claudio Aballay, Luis Quezada, Miguel Alfaro, Guillermo Fuertes, Marc Dahmen and Manuel Vargas. **P. 219**

Power Scheduling with Interruptions for Residential Demand in Smart Grid. Sebastián Taboh, Isabel Méndez-Díaz and Paula Zabala. **P. 229**

Residents' perception from a Brazilian municipality about the COVID-19 social distancing period. Marcele Elisa Fontana, João Paulo Santos Aragão and José Leão. **P. 244**

Computational system for quantitative intra-criterion evaluation in subjective criterion. Marcele Elisa Fontana and Vilmar Santos Nepomuceno. **P. 256**

Mineração de processos e aprendizado de máquina aplicado ao processo de empréstimos pessoais. Pedro Boareto and Silvana Detro. **P. 267**

Modelos de optimización para la planeación táctica de la operación de recolección de residuos sólidos: Caso de estudio en Colombia. Angie Paola Vargas, Santiago Jaramillo, Francisco Rangel, Daniel Villa and Juan G. Villegas R. **P. 281**

Prediction of Viscoelastic Behavior of LDPE Produced in High-Pressure Tubular Reactors. Maira Dietrich, Adriana Brandolin, Claudia Sarmoria and Mariano Asteasuain. **P. 296**

Efficiency analysis and cavitation prediction: Choice of the most suitable propeller for a Brazilian Navy ship. Igor Pa Costa, Sérgio Mn Maêda, Luiz Fhsb Teixeira, Arthur Pa Costa, Carlos Fs Gomes and Marcos Santos. **P. 300**

Comparative analysis between waterjet and conventional propulsion: A new possibility for use in Brazilian Navy Ships. Igor Costa, Sérgio Mn Maêda, Luiz Fhsb Teixeira, Arthur Pa Costa, Carlot Fs Gomes and Marcos Santos. **P. 312**

System dynamics for flood impact assessment. Case study of two municipalities in South America. Nicolas Giedelmann Lasprilla, Carla Andrea Ocampo Terceros, Elyn L Solano Charris and William J Guerrero Rueda. **P. 326**

Análisis multicriterio aplicado a la selección de un Plan Agregado de Producción. Luciana Tabone, Verónica Mortara, Antonio Morcela, Ignacio Boloquy and Jacqueline Bounoure. **P. 330**

A Computer Vision based Gaze Following Application: Contribution in COVID-19 Scenario. George Martins Silva, Emannuell Dartora Cenzi, Matheus Henrique Sanches Maziero, Marcelo Rudek and Anderson Luis Szejka. **P. 343**

A production planning MILP optimization model for a manufacturing company. Juan Antonio Cedillo-Campos, Neale R. Smith, Rosa G. González-Ramírez, Julio Alonso Stocker, Joaquin Alonso Stocker and Ronald G. Askin. **P. 354**

Alistamiento de pedidos en un almacén de comercio electrónico: Una revisión. Fabian Alexander Torres Cardenas, Carlos Eduardo Diaz Bohorquez, Katia Lineth Merlano Canoles and Karina Lizzeth Castellanos Pico. **P. 366**

O impacto da pandemia COVID-19 nas operações econômicas da "Indústria de Alimentos" no Brasil: Uma Pesquisa documental sobre passado, presente e o futuro. Gleison Hidalgo Martins, Evelin Bortolon and Sonia Ferreira Martins. **P. 381**

An operational planning model to support first mile logistics for small fresh-produce growers. Alvaro M. Majluf-Manzur, Rosa Guadalupe Gonzalez Ramirez, J. René Villalobos and Raimundo Velasco Paredes. **P. 396**

Digital Twin e PHM para Otimização de Níveis de Inventário. Joceir Chaves, Eduardo Loures, Eduardo Santos, Julio Silva and Ricardo Kondo. **P. 411**

Hybrid method PROMETHEE-SAPEVO-M1: multicriteria evaluation of River Combat Vessels to support Amazon defense. Miguel Moreira, Marcos Santos and Carlos Gomes. **P. 420**

Analysis of Packaging Losses in Cocoa Butter Production. Amanda Morais Almeida, Aline Patricia Mano and Sérgio Renato Teixeira Nascimento. **P. 435**

Diretrizes para projetos de IIoT em contexto CPS. Júlio Silva, Eduardo Loures, Eduardo Santos, Ricardo Kondo and Joceir Chaves. **P. 445**

Review: Cadenas de Suministro, desde la colaboración de eslabones a la gestión de cadenas sustentables. Natacha Pino. **P. 458**

Applying a Decision Model to Evaluate the Influence of Digital Transformation Technologies on TOGAF Architecture Principles. Izabelle C. Hannemann de Freitas, Sarah G. Rodrigues, Eduardo de Freitas R. Loures and José Marcelo A. P. Cestari. **P. 473**

El gasto energético de los hogares en Argentina: ¿por qué estudiarlo para mejorar la eficiencia energética? María Florencia Zabaloy and María María Ibáñez Martín. **P. 486**

A branch and bound method to minimize the total flow time in a permutation flow shop with blocking and setup times. João V. S. Robazzi, Marcelo S. Nagano and Mauricio I. Takano. **P. 490**

Suporte a tomada de decisão em healthcare usando BPMN e DMN. Pedro Boareto, Silvana Detto and Eduardo Santos. **P. 500**

Mathematical Modeling of ARGET Copolymerization of Styrene and Acrylonitrile. I: Experimental Validation. Cecilia Fotunatti, Claudia Sarmoria, Adriana Brandolin and Mariano Asteasuain. **P. 515**

Mathematical Modeling of ARGET Copolymerization of Styrene and Acrylonitrile. II: Efficient Calculation of Bivariate Distributions using Parallel Computing. Esteban Pintos, Cecilia Fortunatti, Adriana Brandolin, Claudia Sarmoria and Mariano Asteasuain. **P. 525**

ERP Integration with Performance Analytics: a Systematic Literature Review. Thais C. Pfitzreuter and Edson Pinheiro De Lima. **P. 536**

Avaliação de Interoperabilidade Empresarial: Uma revisão sistemática da literatura. Angélica Duarte Lima and Eduardo de Freitas Rocha Loures. **P. 550**

Evaluación de la incorporación de residuos de caucho en hormigones para elementos de protección vial. Ana Giselle Cressa and Carlos Baronetto. **P. 563**

Increasing productivity of a beef production line using Lean 6 Sigma. Martha Ramírez-Valdivia and Viviana Vásquez. **P. 575**

COVID-19 Pandemic Effects on the Idiosyncratic Risk of the Brazilian and Emerging Markets. Andre Assis de Salles. **P. 590**

Gas turbines inlet air cooling: mathematical analysis of Brazilian Navy's ships propulsion efficiency. Pedro M Diniz, Alex Gimenez, Sérgio M N Maêda, Igor P A Costa, Carlos F S Gomes and Marcos Santos. **P. 601**

Reducing heat emission in discharge ducts and increasing the global energy efficiency through energy cogeneration. Alex Gimenez, Pedro M Diniz, Igor P A Costa, Sérgio M N Maêda, Carlos F S Gomes and Marcos Santos. **P. 613**

Process Mining and Value Stream Mapping: an incremental approach. Mario Nawcki, Gabriel Zanon, Lícia Santos, Eduardo Santos, Anderson Szejka and Edson Lima. **P. 625**

Agile DMAIC Cycle: An Approach Based on Process Mining. Renan Prado, Wilson Portela, Márcio Catapan and Eduardo Portela. **P. 639**

Environmental impact assessment of industries through a multicriteria decision-making analysis. Juan Martín Mainardi-Remis, Dolores Gutiérrez-Cacciabue and Verónica Beatriz Rajal. **P. 654**

Exact resolution of the Vehicle Routing Problem with Flexible Time Windows. Lucía Barrero, Rodrigo Viera, Franco Robledo, Claudio Riso, Sergio Nesmachnow and Andrei Tchernykh. **P. 658**

Determinants of Smart city commitment among citizens from Bahía Blanca, Argentina. María Verónica Alderete. **P. 673**

Adecuada asignación de los recursos en sistemas de servucción bajo enfoque Lean Services: caso de estudio industria de la hospitalidad. Hernando Garzón Saenz and Andres Redchuk. **P. 690**

Aportes del enfoque Multimetodológico a la gestión de problemáticas derivadas del COVID-19. Avances para una intervención sistémica en grupos poblacionales. Hernán Van Straaten, Melany Segarra Marinetti and Maria Alejandra Castellini. **P. 705**

Modelo multicritério de apoio a tomada de decisão, baseado em Sistema de Informação Geográfico, para a gestão de acidentes de trânsito. Antônio Bezerra, Murilo Damasceno, Cristiany de Souza, Joana Peixoto, Thomas Gonçalo and Eric Ferreira. **P. 720**

Análise das dimensões da inovação pela ótica das camadas de gestão e operacionais. Osvaldo Garcia, George Silva, Diego Nascimento and Eduardo Rocha Loures. **P. 735**

Transición Energética: Interacciones estratégicas ante la redistribución (o no) de impuestos. David-Alejandro Rivera-Correa and Damián-Emilio Gibaja-Romero. **P. 747**

Transparência governamental em tempos de pandemia do COVID-19. Alcenir Vergilio Negri. **P.769**

Current problems to achieve interoperability, influenced by the process domains, difficulties and challenges for the logistics area in its horizontal and vertical integration. Tainá da Rocha, Arthur Beltrame Canciglieri, Anderson Szejka and Osiris Canciglieri Junior. **P. 777**

Un modelo de medición de la calidad del servicio: Caso de una empresa de mantenimiento de motores. Pedro Palominos, Juan Hernandez, Luis Quezada, Astrid Oddershede and Claudio Macuada. **P. 786**

Simulação do agendamento de horários em um restaurante universitário e seu impacto no tempo de espera em filas. Thayse Duarte de Oliveira, Gustavo Valentim Loch, Tiago Lino Bello, Daniela Miray Igarashi, Lucas Lamy, Ivan Moyses Guimarães and Gilmar Schewtschik Filho. **P. 792**

Generación de valor en el área de Finanzas de una organización de servicios de salud. Luciana Tabone, Verónica Mortara and Alicia Zanfrillo. **P. 807**

A study on a new hybrid metaheuristic based on the black hole algorithm for clustering problems. Felipe Kauai, José Pécora Junior and Leonardo de Lima. **P. 822**

Forecasting Demand in Supply Chain for Automotive Spare Parts: Preliminary Literature Review. Lourdes Loza-Hernández, Ma. de Lourdes Nájera López, Javier García-Gutiérrez, Rubén Vázquez Carbajal and Victor Sánchez Guzmán. **P. 835**

Atributos em modelos de maturidade para cadeias de suprimento inteligentes. Gabriella Moreira, Lucas Coelho, Vinícius Comin, Silvana Detto and Eduardo Portela. **P. 851**

Estudio de capacidad de producción en sistemas de producción de calzado basado en simulación. Florencia Dornes, Daniel A. Rossit and Nancy B. López. **P. 865**

Medição de desempenho baseado em dados para máquinas: Revisão sistemática de literatura. Gleison Hidalgo Martins, Pablo Deivid Valle, Silvana Pereira Detto and Fernando Deschamps. **P. 875**

Simulación de eventos discretos para la estimación del nivel de servicio en un laboratorio de análisis de materiales. Josué Rojas-Rodríguez, Gastón Vertiz-Camaron, Jenaro Nosedal-Sánchez and Javier García-Gutiérrez. **P. 890**

Despacho óptimo de buses eléctricos bajo incertidumbre en los tiempos de viaje. Karam Kharrat, Víctor Albornoz and Linco Nanco. **P. 905**

Filosofia Lean em ambientes acadêmicos: Um estudo de caso em uma organização de nível técnico. Jordana Paula Berkenbrock, Edson de Carvalho Ramos, Marcelo Trentin and Flavio Trojan. **P. 917**

Minimizing total implementation cost of a 2-D indoor localization system with a constant accuracy for underground mine tunnels. Andrea Teresa Espinoza Pérez, Daniel Rossit and Oscar C. Vásquez. **P. 931**

Utilização do método PDCA para melhoria de processos: estudo de caso em um centro de distribuição ali-mentícia. Maressa Fontana Mezonzi and Sergio Luiz Ribas Pess. **P. 937**

Utilization of Rice Husk (OryzaSativa) for the Elaboration of an Agglomerate Material for the Construction of Housing in Cucuta, Norte de Santander, Colombia. Lizeth Alfonsina Portilla Villarreal, José Alfredo Gutiérrez Durán, Yerson Fabián Quitian Osorio and Maribel Gómez Peñaranda. **P. 950**

Gestión de inventarios para una pyme. Paloma Lillo, Cecilia Montt, Astrid Oddershede, Luis Quezada and Alejandra Valencia. **P. 958**

Current Issues in Flexible Manufacturing using Multicriteria Decision Analysis and Ontology Based Interoperability in an Advanced Manufacturing Environment. Matheus Beltrame Canciglieri, Athon Francisco Curi Staben de Moura Leite, Eduardo de Freitas Rocha Loures, Osiris Canciglieri Junior, Y.M. Goh and Radmehr Monfared. **P. 964**

Estudio de Caso sobre el Cumplimiento de los Principios de Gestión de la Calidad Según la Norma ISO 9001 Versiones 2008 y 2015, de los Empleados de Dos Empresas Cafeteras de Nariño Colombia. Lizeth Alfonsina Portilla Villarreal, Martha Ramírez-Valdivia and Lorena Alexandra Portilla Villarreal. **P. 977**

Sistema innovador de producción de agua segura: análisis económico y comparación con otras alternativas. Jorge Emilio Almazan, Miguel Cervantes-Schamun, Dolores Gutierrez Cacciabue and Verónica Beatriz Rajal. **P. 995**

Assessing funding options for digital transformation: a study with specialists. Rafaela Plan-tes Pavloski, Fernando Deschamps, Edson Pinheiro de Lima, Rosemary Francisco and Eduardo Rocha Loures. **P. 999**

Implementação de um modelo de simulação na indústria moveleira. Angelo Rocha, Fernando Deschamps and Silvana Detto. **P. 1005**

A Multiple-Criteria Directional Measure for Resource Management in Hospitalizations. Thyago C. C. Nepomuceno, Wilka M. N. Silva and Késsia T. C. Nepomuceno. **P. 1016**

Long-term evaluation of energy efficiency measures in transport, case study Paraguay. Manuel Olmedo, Eduardo Ortigoza, Diana Valdez, Richard Ríos and Victorio Oxilia. **P. 1022**

Método multicriterio grupal para decisiones rutinarias. José Francisco Zanazzi, José Luis Zanazzi and Daniel Pontelli. **P. 1034**

SPECIAL SESSION: INDUSTRY 4.0

Increasing Confidence in Industry 4.0 through new Software Verification and Validation Techniques. Martin Larrea and Dana Urribarri. **P. 1039**

Modelling the Dynamics of a Smart Factory. Marisa Sánchez, Daniel Rossit and Fernando Tohmé. **P. 1054**

Integración de ROS y Tecnomatix para el desarrollo de gemelos digitales en sistemas de manufactura flexible. Carolina Saavedra Sueldo, Sebastian A. Villar, Mariano De Paula, Silvia B. Urrutia and Gerardo G. Acosta. **P. 1069**

Data Analytics support for the Integrated Planning of Cutting Orders in Banana Crops harvesting: a case study in Colombia. Carlos Paternina-Arboleda, Yanelis Payares-Osorio, Luis E. Ramirez-Polo and Benjamin Thomas Hazen. **P. 1084**

A proposal Roadmap to implement Industry 4.0 in SMEs. Jose Mauricio Mottin de Andrade, Eduardo de Freitas Rocha Loures, Anderson Luiz Szejka and Osiris Canciglieri Junior. **P. 1097**

Digital transformation framework for adequacy of maintenance systems to Industry 4.0. André Venâncio, Eduardo Loures, Ricardo Diogo, Alyson Lumikoski, Neri dos Santos and Fernando Deschamps. **P. 1109**

The emergence of new business and operating models under the Industrial Digital Paradigm Industrial Internet of Things (IIoT), Platforms, and Artificial Intelligence/Machine Learning (AI/ML). Federico Walas Mateo and Andres Redchuk. **P. 1123**

Análise de Maturidade da Indústria 4.0: foco em Países Emergentes. Gustavo de Melo Silva, Gilson Adamczuk Oliveira, Marcelo Gonçalves Trentin and Dalmarino Setti. **P. 1133**

Developing a Resource-based Manufacturing Process Capability Ontology. Dusan Sormaz, Arkopaul Sarkar, David Koonce and Sharmake Farah. **P. 1147**

Process Plan Reasoning based on SPARQL Extension. Arkopaul Sarkar and Dusan Sormaz. **P. 1162**

A Novel Framework for the Shop-floor Scheduling Nervousness. Juan M. Novas. **P. 1178**

Modelo de Maturidade PLM (Product Lifecycle Management) com Conceitos da Indústria 4.0 – Avaliação com base no método AHP. André Luiz Micosky, Kássio Cabral Pereira Dos Santos, Eduardo de Freitas Rocha Loures and Osiris Canciglieri. **P. 1182**

Desarrollo de herramientas para la gestión óptima de envases vacíos de fitosanitarios y sus contenidos residuales. Antonela Elisa Sorichetti, Mariana Gonzalez Prieto, Andrea Alejandra Savoretti, Silvia Elena Barbosa and José Alberto Bandoni. **P. 1197**

Operation Skipping Flow Shop Scheduling and Industry 4.0. Daniel Alejandro Rossit, Adrián Toncovich, Diego Gabriel Rossit and Sergio Nesmachnow. **P. 1212**

Future research agenda to understanding the Sustainable Business Model in Industry 4.0. Grazielle Fatima Gomes Teixeira, Osiris Canciglieri Junior and Anderson Luis Szejka. **P. 1222**

Universities Best Practices in Open Innovation and R&D. Michele Marcos de Oliveira, Osiris Canciglieri Junior and Bernardo Reisdorfer Leite. **P. 1237**

Revisiting the Product-Process Matrix: incorporating distributed manufacturing concepts. Guilherme Brezinski, Alexandre Helmann, André Venâncio, Sérgio Gouvêa, Eduardo Loures and Fernando Deschamps. **P. 1250**

Integrated production and maintenance planning: a systematic literature review. Nicollas Luiz Schweitzer de Souza, Lucio Galvão Mendes, Eugênio Strassburger Rovaris, Enzo Morosini Frazzon and Lynceo Falavigna Braghirolli. **P. 1264**

Development of a Methodology to Analyze Implementation Patterns of Industry 4.0 Technologies in the Santa Fe Region. Oscar Quiroga, Samuel Osina and Mariana Díaz. **P. 1279**

Evidências da Indústria 4.0 no setor eletroeletrônico brasileiro: um estudo multicase a partir da literatura. Fernando Schenatto, Fabiano Carniel and Luís Alberti. **P. 1293**

A Fast and Elitist Multi-objective Genetic Algorithm for Seru Production Assignment Problem Considering Worker Skills and Proficiency. Sofia Magdalena Escobar Forero and Ciro Alberto Amaya Guio. **P. 1310**

Proceso de toma de decisión multicriterio aplicado a máquinas de una línea de producción. Félix Fernández, Eduardo Ortigoza, Victorio Oxilia, Lucas Cáceres, Rodrigo González and Roberto Fariña. **P. 1325**

Estrategias de flexibilización de los sistemas de producción en la industria 4.0: un marco para la caracterización. Diana C. Tascón and Gonzalo Mejía. **P. 1341**

Factores que influyen en la adaptación de la Industria 4.0 a la gestión del mantenimiento en las empresas colombianas. Leidy Marcela Duenas Ramirez, Gustavo Adolfo Villegas Lopez, Sebastian Castiblanco Tique, Carlos Andres Castaño Restrepo, Martin Andres Rosendahl Garcia, Alejandro Lopez Giraldo and Luisa Fernanda Ortiz Vasquez. **P. 1356**

SPECIAL SESSION: PROCESS INDUSTRY

Desarrollo de herramientas de soporte a la toma de decisiones en una planta de producción de jugos concentrados. Anibal Blanco, Susana

Moreno, Carolina Taraborelli, Flavio D'Angelo, Facundo Iturmendi and Alberto Bandoni. **P. 1369**

Optimización de la Trazabilidad en la Cadena de Suministro de la Carne. Bárbara Verónica Schmidt and Marta Susana Moreno **P. 1384**

Ajuste de parámetros cinéticos de la reacción inversa del gas de agua (RWGS) en la producción de metanol. Constanza Genovese, Ignacio Costilla, Carlos Eugenio Gigola and Nelida Beatriz Brignole. **P. 1399**

Modelo integrado de planificación de decisiones del desarrollo de operaciones upstream. Luciano Benvenutti, Daniel Oscar Borio and Jose Alberto Bandoni. **P. 1412**

Propuesta de una biorrefinería en una industria azucarera cubana aprovechando la biomasa. Ana Celia de Armas Martínez, Yaillet Albernas Carvajal, Erenio González Suárez and Gabriela Corsano. **P. 1416**

Modelado matemático de una planta piloto de producción de sidra para la toma de decisiones. Facundo Iturmendi, Carolina Taraborelli, Juan Ignacio Laiglecia, Natalia Bongiovani and Flavio D'Angelo. **P. 1420**

A Nonlinear Parameter Estimation for Biodiesel Production with Nannochloropsis oceanica CCALA 978. Juan Ignacio Laiglecia, Natalia Bongiovani, Facundo Iturmendi, Cecilia Popovich and Patricia Leonardi. **P. 1432**

Programación de Operaciones Eficiente de un Caso de Estudio Real de la Industria Farmacéutica mediante una Metodología de Descomposición Matemática-Algorítmica. Josías Stürtz and Pablo Marchetti. **P. 1436**

Análisis de incertidumbre en modelos de celdas de combustible de hidrógeno de tipo PEM. Ignacio Pérez Correa, Pablo Giunta and Javier Francesconi. **P. 1440**

Robust data reconciliation applied to uncertainty steady state model. Claudia Llanos and Mabel Sánchez. **P. 1451**

Biogas una alternativa Neuquén. Ivone Elisabet Carroza, Gisela Magali Sanchez, Yesenia Martina Perez, Marcela Noemi Gatti, Alberto Camacho and Jose Luis Boiardi. **P. 1466**

[SPECIAL SESSION: FORESTRY](#)

Tendencias climáticas de la Región Pampeana (Argentina) durante 1960-2019. Federico Ferrelli, Andrea Soledad Brendel, María Cintia Piccolo and Gerardo Miguel Eduardo Perillo. **P. 1476**

Variabilidad climática de la Región Pampeana (Argentina) en el contexto de cambio climático. Andrea Soledad Brendel, Federico Ferrelli and Maria Cintia Piccolo. **P. 1480**

Disminución de la Disponibilidad de Agua Potable por Expansión de la Forestación, en el Sector Costero Oriental de la Provincia de Buenos Aires, Argentina. Leonardo Sánchez Caro, Silvina Claudia Carretero, Fernanda Julia Gaspari and Alfonso Martín Rodríguez Vagaría. **P. 1484**

Energy optimization for the operation of a sawmill. Nicolas Vanzetti, Nestor Steitzer, Gabriela Corsano and Jorge Marcelo Montagna. **P. 1499**

A column generation based algorithm for solving the log transportation problem. Maximiliano R. Bordón, Jorge Marcelo Montagna and Gabriela Corsano. **P. 1514**

Problema de Recogida y Entrega en la Industria Forestal: nuevos modelos y estudio de su performance. Luciana Melchiori, Graciela Nasini, Marcelo Montagna and Gabriela Corsano. **P. 1529**

Desarrollo de un sistema de programación de ordenes de trabajo con restricciones de sincronización para una empresa de la agroindustria de flores. Freddy López, Alfonso Sarmiento and William Guerrero. **P. 1544**

Producción de biogás y modelado del potencial metanogénico de residuos porcinos y co-sustratos. Marcos Astorga, Margarita Cesano, Marcela Noemí Gatti and Alberto Camacho. **P. 1548**

Evaluación del rendimiento económico y volumétrico de una planificación estratégica en un patrimonio forestal del Norte de la Provincia de Misiones. Mathías Isaac López, Enzo Martín Sanzovo, Julio Eduardo Arce, Hugo Daniel Reis and Diego Ricardo Broz. **P. 1557**

An integrated approach for solving the bucking and routing problems in the forest industry. Maximiliano R. Bordón, Jorge Marcelo Montagna and Gabriela Corsano. **P. 1563**

Uniformidad en la distribución de aplicación de diferentes diseños de pastillas de pulverización. Victor H. Merani, Matilde Mur, Facundo Guilino, Larrieu Luciano, Juan Manuel Vazquez, Mariana Bethouart and Roberto Balbuena. **P. 1578**

Evaluación del Endocarpio de Coco (cocos nucifera) como Sustrato en el Cultivo de Pleurotus Ostreatus en el Municipio de Villa del Rosario, Norte de Santander Colombia. Lizeth Alfonsina Portilla Villarreal, Carlos Jahir Rodríguez Estupiñán, Juan Carlos Mora Santos and Lorena Alexandra Portilla Villarreal. **P. 1592**

Pulverizaciones agrícolas: Comparación de metodologías para su evaluación. Victor H. Merani, Matilde Mur, Facundo Guilino, Larrieu Luciano, Florencia Pi Puig, Juan Manuel Vazquez and Roberto Balbuena. **P. 1606**

Systematic Literature Review of Water-Energy Nexus: An Overview of the field and analysis of the top 50 influential papers. Gabriel Pereira, Arturo Gonzalez and Richard Germán González. **P. 1610**

Efecto del coadyuvante sobre la prestación de diferentes boquillas en espigas de Trigo. Matilde Mur, Victor Merani, Facundo Guilino, Larrieu Luciano, Juan Manuel Vazquez and Roberto Balbuena. **P. 1626**

SPECIAL SESSION: **HEALTH**

Eficiencia espacial en la atención primaria de la salud en Bahía Blanca. Maria Florencia Arnaudo, Fernando Pablo Lago, Alberto Bandoni and Guillermo Durand. **P. 1642**

Comparación de Métodos Multicriterio Grupales: Procesos DRV vs AHP grupal. El caso de la gestión sobre residuos patógenos. Nadia Ayelen Luczywo, José Luis Zanazzi and Catalina Lucía Alberto. **P. 1654**

National Health Systems and doubling time of number of deaths by COVID-19 Coronavirus. Diego Muñoz-Godoy, Samuel Ponce, Naudy Leal, Macarena Alborno, Manuel Vargas and Guillermo Fuertes. **P. 1668**

Modelación del proceso de programación de pacientes en listas de espera en un hospital público de Chile. Jaime Bustos, José Luis Toro and Sonia Salvo. **P. 1677**

Determinación de los porcentajes de aportación en el sistema de jubilación de una institución de educación superior mediante un modelo de optimización. Marco Antonio Montufar Benitez, Eva Selene Hernandez Gress, José Luis Mota Reyes, Hector Rivera Gomez and Octavio Castillo Acosta. **P. 1681**

SPECIAL SESSION: **FOOD**

Biofilm Formation on Ultrafiltration Membranes by Yeast Strains Isolated from Apple Juice Processing Industries. María del Rosario Agustín, María Clara Tarifa and Lorena I. Brugnoli. **P. 1692**

Modelado Cinético de la Degradación Térmica de Biocompuestos y de Color en Tomate Triturado. Emiliano E. Badin, Pablo D. Ribotta and Alejandro R. Lespinard. **P. 1696**

Evaluación reológica y térmica de oleogeles formulados con ceras de girasol y aceite de

girasol alto oleico. Cintia Redondas, Amalia Carelli and Erica Bäumlér. **P. 1709**

Efecto de la Sustitución Parcial de NaCl con KCl Sobre las Propiedades Sensoriales de Queso Port Salut. Tomás Ramón Gill, Hernán Ramón Allasia, Guillermo Ernesto Hough, Mario Nicolas Lanteri and Alejandro Rafael Lespinard. **P. 1724**

Bioactividad de extractos de bagazo de cerveza. Diana Potes Vecini, Juliana Piña, Mónica Nazareno and Consuelo Pacheco. **P. 1728**

Efecto de la temperatura de secado en la microencapsulación de antioxidantes naturales. Macarena Ortiz, Juliana Piña, Mónica Nazareno and Consuelo Pacheco. **P. 1733**

Estudio cinético de parámetros de calidad nutricional y sensorial en leche tratada térmicamente. María del Milagro Mercatante, Emiliano Emanuel Badin, Javier Ramiro Arballo and Alejandro Rafael Lespinard. **P. 1742**

Nanostructured lipid carrier developed with propolis wax residues. Gabriela Krepper, Centurión María Eugenia and Erica Bäumlér. **P. 1753**

Relationship between microstructure, rheological behavior and kinetic stability of oleo-gel emulsions produced with recovered and commercial sunflower waxes. Julie Merchan Sandoval, Amalia Carelli, Erica Bäumlér and Camila Palla. **P. 1759**

Simulación matemática de un Desolventizador-Tostador industrial. Mauricio M. Coletto, J. Alberto Bandoni and Anibal M. Blanco. **P. 1769**

Comparison between Clarke & Wright and Nearest Neighbor methods on thermal performance of Cold Chain products during generation of distribution route. Luíza Bezerra, Vanina Silva and Diogo Silva. **P. 1784**

Evaluación tecnológica en bodega de una levadura vínica patagónica previamente propagada

en un sustrato no convencional. Sebastian Bravo, Diana Constenla and Adriana Caballero. **P. 1799**

Extracción de compuestos bioactivos de frutas cv. Albion tratadas con ozono en fase acuosa y almacenadas en refrigeración, y evaluación de sus propiedades antioxidantes. Eunice V. Contigiani, Gabriela M. Jaramillo Sánchez, Ángela R. Romero Bernal, Paula L. Gómez and Stella M. Alzamora. **P. 1805**

Desarrollo de yogur descremado deslactosado reducido en sacarosa mediante hidrólisis enzimática. Marianina Perez Cenci, Rocío Celeste Dominguez, Agustina Rocío Fernandez and Guadalupe Fuertes. **P. 1818**

Ultrastructural Damage and Mycotoxin Accumulation of *Aspergillus flavus*, *A. parasiticus* and *Fusarium verticillioides* as Affected by Flavonoids: a Comparative Study. Paula Sol Pok, Silvia Liliana Resnik and Stella Maris Alzamora. **P. 1832**

Efecto del salado sobre las propiedades reológicas y la estructura de filetes de merluza (*Merluccius hubbsi*) utilizando diferentes métodos. Marion Daniela Marchetti, Analía Belen Garcia Loredó and María Isabel Yeannes. **P. 1846**

Evaluación de la Viabilidad de Cepas Probióticas de *Lactobacillus* Encapsuladas en Micropartículas de Pectina para uso en Matrices Vegetales. María Clara Tarifa, Cristian Piqueras, Diego Genovese and Lorena Brugnoli. **P. 1860**

Modelling Planetary Ball Milling of Rice Starch. Luciana González, Maria Loubes and Marcela Tolaba. **P. 1865**

Influence of olive mill waste polyphenols levels on carotenoid production by *Rhodotorula mucilaginosa*. Carolina Ghilardi, Amalia Antonia Carelli and Maria Virginia Borroni. **P. 1876**

Gelificación del caseinomacropéptido en presencia de sales de calcio (cloruro de calcio y acetato de calcio). Karina Loria, Ana M.R. Pilosof and María Edith Farías. **P. 1882**

Evaluación composicional de bagazo de diferentes estilos de cerveza artesanal para su valorización. Luciana M. Rodriguez, Diana T. Constenla and Ethel E. Pérez. **P. 1897**

Inactivación de *Fusarium graminearum* en cebada cervecera (*Hordeum vulgare* L.) mediante ozono en fase acuosa: potencial aplicación en la etapa de malteado. Bibiana Zuluaga Calderón, Stella Maris Alzamora, Héctor Horacio Lucas González and María Bernarda Coronel. **P. 1911**

Valorización de residuos provenientes del salado-madurado de anchoíta (*Engraulis anchoita*). Marion Daniela Marchetti, Rolando Jimenez Lugo and Marina Czermer. **P. 1922**

Arsénico en agua y alimentos: determinación del perfil de riesgo en Argentina. Silvina Perez, Marion D Marchetti and Alejandra Tomac. **P. 1926**

Microbioma de *Engraulis anchoita* salada-madurada. Silvina Perez, Maria I Yeannes and Silvia E Murialdo. **P.1931**

Efecto del ozono en fase acuosa sobre las ceras epicuticulares y el color de arándanos (*Vaccinium corymbosum* L.,cultivar O'Neal). Gabriela M. Jaramillo Sánchez, Eunice V. Contigiani, Stella M. Alzamora and Patricio R. Santagapita. **P. 1935**

Influencia de cultivos autóctonos iniciadores de la fermentación alcohólica sobre atributos sensoriales de vinos Patagónicos. Sebastian Bravo, Silvana del Mónaco, Adriana Caballero, Yolanda Curilen and Manuel Morales. **P. 1950**

Evaluación de emulsiones filmogénicas a base de aislado de soja y cera de abeja. Florencia Salaberría, Agustin Benestante, Ethel Pérez and Erica Baümler. **P. 1965**

Caracterización de propóleos como fuente lipídica con compuestos activos. Florencia Salaberría, María Soledad García Paoloni, Marcelo Pistonesi, Erica Baümler and Ethel Pérez. **P. 1976**

Afinidad del caseinomacropéptido con el CaCl₂ a pH neutro. Karina Loria, Ana M.R. Pilosof and María Edith Farías. **P. 1980**

SPECIAL SESSION: MANAGEMENT

Project Management Process Resilience: Assessing and Improving the Project Review Process Using FRAM. Vinicius Bigogno Costa, Moacyr M. Cardoso Jr. and Ligia Maria Soto Urbina. **P. 1992**

Medios de pago electrónicos y evasión tributaria: el caso argentino. Florencia Verónica Pedroni, Gabriela Pesce and Anahí Briozzo. **P. 2007**

Building High Performance Teams. Thais C. Pfitzenreuter, Edson Pinheiro de Lima and José R. Frega. **P. 2022**

Human Resources 4.0: Use of Sociometric Badges to Measure Communication Patterns. Regina Moirano, Marisa A. Sanchez, Libor Štěpánek and Gastón Vilches. **P. 2037**

An Optimization Model for University Course Timetabling. A Colombian Case Study. Jaén Suárez-Rodríguez, Juan C. Piña, Laura Malagón-Alvarado, Valentina Blanco, Melissa Correa, Laura De La Rosa, Mariana Lopera, Juan Valderrama and Carlos Vega-Mejía. **P. 2052**

Identificação de fatores para avaliação da qualidade de energia elétrica: os impactos na geração, distribuição e setores de consumo. Virginia Thomasi, Heloísa Pereira Burin, Julio Cezar Mairesse Siluk and Carmen Brum Rosa. **P. 2067**

Diseño de una red de domicilios en tiendas de barrio para abastecimiento de alimentos en tiempos de COVID-19: Un enfoque de optimización lineal. Daniela Granados, Gonzalo Mejía, Laura Tinjaca and Natalia Cárdenas. **P. 2080**

Study of the location of a second fleet for the Brazilian Navy: Structuring and mathematical modeling using SAPEVO-M and VIKOR methods. Isaque Dp Almeida, José Vp Corriça,

Arthur Pa Costa, Igor Pa Costa, Sérgio Mn Maêda, Carlos Fs Gomes and Marcos Santos. **P. 2095**

Localización de proveedores de salud en zonas rurales en países en desarrollo: Un enfoque de programación lineal entera mixta. Daniela Granados, Gonzalo Mejía, Gabriela Rico, Daniela Cuéllar, Nicolás Montes and Tania González. **P. 2108**

Multicriteria analysis by the PROMETHEE-SAPEVO-M1 method: a decision analysis for the closure of a bank agency. Miguel Moreira, Marcos Santos and Carlos Gomes. **P. 2123**

Development of a methodological proposal for the creation of strategic maps incorporating feasible futures. Miguel González, Quezada Luis, Pedro Palominos, Astrid Oddershede and John Rios. **P. 2137**

Toma de decisiones multicriterio para identificar los procesos de mayor impacto en la continuidad operacional en una empresa sanitaria en contexto de pandemia. Claudio Macuada, Astrid Oddershede, Luis Quezada, Pedro Palominos and Cecilia Montt. **P. 2141**

Inventory management of aftermarket: case study. Victor Sánchez Guzmán and Lourdes Loza-Hernández. **P. 2146**

Modelo de simulación de la gestión de un Job Shop. Una herramienta de soporte a la toma de decisiones. Jaime Giraldo, Omar Castrillon and Jaime Arango. **P. 2159**

A strategic reference model for the competitiveness of the port supply chain. Luis M. Ascencio, Rosa G. Gonzalez Ramirez and Stefan Voss. **P. 2174**

Adaptation of the Balanced Scorecard to Latin American Higher Education Institutions in the Context of Strategic Management: A Systematic Review with Meta-analysis. Mauricio Hinojosa. **P. 2176**

Visão Baseada em Recursos: O uso da tecnologia Blockchain na Gestão do Conhecimento. Talita Frozza and Andressa Maria Corrêa. **P. 2191**

Key Factors for the Implementation of New Technologies in Manufacturing Systems – Insights from Case Studies. Paulo Henrique Brunheroto, Cassiano Souza Beller, Fernando Deschamps and Edson Pinheiro de Lima. **P. 2206**

How do Industry 4.0 technologies impact performance objectives? Results of an empirical survey in large enterprises and SMEs of the Curitiba Metropolitan Region. Paulo Henrique Brunheroto and Fernando Deschamps. **P. 2221**

Transformação digital na prestação de serviços: mapeamento de tecnologias. Talita Frozza, Fernando José Avancini Schenatto and Edson Pinheiro de Lima. **P. 2236**

Explorando lacunas em modelos de maturidade existentes para avaliação da cadeia de suprimentos inteligente – uma revisão literária. Adalberto dos Santos, Eduardo Alves Portela Santos and Silvana Pereira Detro. **P. 2249**

Service network design problem in freight transportation. A literature review. Jessica Jazmin Vazquez-Azotea, Javier Garcia-Gutierrez, Lourdes Loza-Hernandez and Ma. De Lourdes Najera-Lopez. **P. 2264**

SPECIAL SESSION: MACHINE LEARNING AND BIG DATA IN INDUSTRIAL PROCESSES

Exploring Machine Learning Integration with Operations Strategy. Thais C. Pfutzenreuter, Nathália R. G. Chamie, Edson Pinheiro de Lima and Sergio E. Gouvea da Costa. **P. 2273**

A Database Curation for Prediction of the Refractive Index in the Virtual Testing of Polymeric Materials by using Machine Learning. Santiago Ariel Schustik, Fiorella Cravero, Ignacio Ponzone and Mónica Fátima Diaz. **P. 2285**

Big data analytics process architecture for manufacturing industries: a literature review. Letícia Alves dos Santos Rosolem, Fernando Deschamps, Edson Pinheiro de Lima and José Marcelo Almeida Prado Cestari. **P. 2300**

SPECIAL SESSION: PRODUCTIVITY

Melhores práticas em eficiência energética em edifícios comerciais: uma discussão sobre modelos existentes. Barbara Bonfim Catapan, Sergio E. Gouvea da Costa and Edson Pinheiro de Lima. **P. 2315**

Análisis de eficiencia de los bancos nacionales de los países del Mercosur en entornos difusos. Claudia Peretto and Cecilia Solange Cáceres. **P. 2320**

Evaluación de la Eficiencia Técnica de los Centros de Atención Primaria Salud en la Ciudad de Bahía Blanca. Facundo Durán, María Eugenia Elorza, Fernanda Villarreal, María Florencia Arnaudo and Pablo Luis Acrogliano. **P. 2324**

SPECIAL SESSION: MECHATRONICS

A Proposal for an Interoperable Data Collection System for Production Control on CNC Machining Lines of a Healthcare Product. Victória R. S. Camargo, Thomas V. B. Amaral, Sofia T. Helena, Matheus Beltrame Canciglieri, Athon Francisco Curi Staben de Moura Leite and Anderson Luis Szejka. **P. 2339**

SPECIAL SESSION: MECHANICAL

Máquina Paletizadora: Processo de Desenvolvimento do projeto. Gabriel Krause, Diogo Belle and Fernando José Avancini Schenatto. **P. 2353**

SPECIAL SESSION: EDUCATION

Teaching Artificial Intelligence using Project Based Learning. Marc Dahmen, Luis Quezada,

Miguel Alfaro, Guillermo Fuertes, Claudio Aballay and Manuel Vargas. P. 2369

Modelización matemática para la toma de decisiones en proyectos interdisciplinarios.
Pablo Carranza. P. 2387

Reestructuración del dictado de materias de Matemática en las carreras de Ingeniería en Alimentos e Ingeniería en Biotecnología.
Griselda R. Itovich and Juan I. Laiglecia. P. 2391

Autoevaluación y Coevaluación para la mejora continua del trabajo en grupo: Aplicación y experiencia en clases virtuales.
Antonella Cavallin and Elda Monetti. P. 2398

Modelo matemático para evaluación adaptativa.
Sebastián Dávila, Óscar Vásquez and Luis Osorio. P. 2417

SPECIAL SESSION: METAHEURISTICS

Optimización por Colonia de Hormigas para el Ruteo del Picking en Almacenes de Múltiples Bloques.
Jose Alejandro Cano, Emiro Antonio Campo, Alexander Alberto Correa-Espinal and Rodrigo Andrés Gómez-Montoya. P. 2423

A decision support tool for the location routing problem during the COVID-19 outbreak in Colombia.
Andres Felipe Martinez Reyes, Carlos Quintero Araujo and Elyn Lizeth Solano Charris. P. 2428

Simulated Annealing metaheuristic approach for generating alternative corridor locations.
Pedro Moreno and Sergio Nesmachnow. P. 2443

Algoritmo evolutivo híbrido basado en la división del espacio de los objetivos para el problema de la mochila bi-objetivo.
Daniel Alejandro Rossit, Máximo Méndez, Mariano Frutos and Begoña González. P. 2458

Redes neuronales LSTM aplicadas a la predicción de oleaje en tiempo real para generación de energía undimotriz en las Islas Canarias.

Carlos Hernández, Máximo Méndez, Ricardo Aguasca-Colomo and Begoña González. P. 2472

Algoritmos genéticos para la toma de decisiones en la cadena de valor apícola.
Luciana Belén Villar, Martín Carlos De Meio Reggiani, Hernán Pedro Vigier and Nélida Beatriz Brignole. P. 2486

Dynamic Order Acceptance and Scheduling Approach for On-demand Production with Additive Manufacturing by Considering Idle Costs.
Qiang Li, David Zhang and Ibrahim Kucukkoc. P. 2501

A Decomposition Approach for the Combined Inventory Routing and Scheduling Problem.
Carlos Franco and Eduyn López-Santana. P. 2515

Resolución de los problemas Order Batching / Picking a través de un Algoritmo Evolutivo.
Fabio Maximiliano Miguel, Mariano Frutos, Máximo Méndez and Fernando Tohmé. P. 2519

Una Metaheurística de Recocido Simulado para Resolver un Problema de Ruteo de Vehículos en la Recolección de Residuos.
Matías Fermani, Diego Gabriel Rossit and Adrián Toncovich. P. 2531

A simulation-based optimization framework for a comparative analysis of different heuristics applied to discrete-event simulation.
Juan Pablo Morandé, Rosa González-Ramirez and Sergio Quijada. P. 2545

Simulated Annealing Algorithm for In-Plant Milk-Run System.
Islam Altin and Aydin Sipahioglu. P. 2561

Aplicación de optimización y metaheurísticas al problema de ruteo de vehículos periódico integrando programación y frecuencia de servicio.
Sergio Esteban Vega Figueroa, Paula Andrea López Becerra and Eduyn López Santana. P. 2577

Un algoritmo de Búsqueda Tabú para el problema de Ruteo de Vehículo Milk Run con ventanas de tiempo (VRPMRTW).
Carlos Eduardo

Díaz Bohórquez, Lina Mayerly Lozano Suarez and Laura Ximena Sanchez Rincón. P. 2581

Periodic vehicle routing with consistency and synchronization constraints for nanostore fulfilment in emerging markets. Andres Gomez, Juan Carlos Rivera and Juan Guillermo Villegas. **P. 2597**

SPECIAL SESSION: SCHEDULING

Nueva representación para la resolución simultánea del batching y scheduling en una planta batch multiproducto. Sergio Ackermann, Yanina Fumero and Jorge Marcelo Montagna. **P. 2602**

Flow-shop con consideraciones energéticas y aplicación de lot-streaming. Florencia D'Amico, Daniel Alejandro Rossit and Mariano Frutos. **P. 2616**

Formulação indexada no tempo e algoritmo heurístico para um problema integrado de localização e sequenciamento. Raphael Kramer and Arthur Kramer. **P. 2630**

Impacto de la productividad y la polifuncionalidad laboral en la gestión de personal: caso aplicado a la industria retail. Silvana Vergara, Jairo Del Villar, James Masson, Natalia Pérez, Cesar Augusto Henao and Virginia González. **P. 2644**

Two-stage stochastic optimization model for personnel days-off scheduling using closed-chained multiskilling structures. Orianna Fontalvo Echavez, Laura Fuentes Quintero, César Augusto Henao and Virginia I. González. **P. 2659**

Beneficios de la polifuncionalidad laboral en la industria retail: Enfoque “k-chaining” con incertidumbre en la demanda. Yessica Mercado Morales and César Augusto Henao. **P. 2672**

Aplicações da Simulação de Monte Carlo em problemas de Programação Linear: uma revisão sistemática da literatura. Jaqueline Marchiore Petri, José Donizetti de Lima and Fernando José Avancini Schenatto. **P. 2687**

2D Nesting and Scheduling in Metal Additive Manufacturing. Ibrahim Kucukkoc, Zixiang Li and Qiang Li. **P. 2702**

A Genetic Algorithm for Flexible Job Shop Scheduling Problem with Scarce Cross Trained Setup Operators. Dolapo Obimuyiwa and Fantahun Defersha. **P. 2717**

Using the k-chaining approach to solve a stochastic days-off-scheduling problem in a retail store. María Abello, Nicole Ospina, Julia De la Ossa, César Henao and Virginia González. **P. 2732**

Heuristic methods for the m-machine blocking flow shop with setup times to minimize hierarchical objective-function. Hugo H. Miyata and Marcelo S. Nagan. **P. 2747**

Heuristics for earliness and tardiness scheduling of identical parallel machines subject to common restrictive due windows. Gustavo A. Rolim and Marcelo S. Nagano. **P. 2762**

The Online Lot Streaming Problem: A Characterization and Solution Approach for Flexible Job Shop Environments. Juan M. Novas. **P. 2777**

Uso de la Programación por Metas y del Proceso Analítico de Jerarquías para la obtención de la mezcla de productos. Claudia Zárate, María Betina Berardi and Alejandra María Esteban. **P. 2781**

Customer order scheduling problem to minimize total tardiness with sequence-dependent setup times. Massimo Pinto Antonioli, Carlos Diego Rodrigues and Bruno de Athayde Prata. **P. 2796**

A Research Direction in Manufacturing Systems Scheduling: A proposal. Fantahun Defersha. **P. 2809**

Modeling and Solving the Total Flow Time Fixed Group Shop Scheduling Problem. Francisco Yuraszeck, Gonzalo Mejía and Jordi Pereira. **P. 2819**

SPECIAL SESSION: SUSTAINABLE

Production Planning with Remanufacturing and Environmental Costs. Luciana Vidal, Pedro Piñeyro, Omar Viera, Paula Martínez and Diego Molina. **P. 2824**

Simultaneous lot-sizing and scheduling with recovery options: problem formulation and analysis of the single-product case. Pedro Piñeyro and Daniel Rossit. **P. 2837**

Planificación de minutas alimentarias para el casino central de una Universidad Pública de Chile: Un enfoque para la reducción de la huella de carbono. Javiera García-Leal, Andrea Teresa Espinoza Pérez and Oscar C. Vásquez. **P. 2849**

Technologies investments in the era of digital transformation and sustainable development. Diego Audrey de Lima Lamezon, Edson Pinheiro de Lima and Sergio Eduardo Gouvea da Costa. **P. 2854**

A mathematical model for the cost optimization of bioethanol production integrated into pulp and paper supply chain– The impact of scale and capacity strategies. Frank Piedra-Jimenez, Natalia G. Tassin, Juan M. Novas and María Analía Rodríguez. **P. 2870**

Relación entre las prácticas de calidad y el desempeño sostenible de cadenas de suministro. Juan M. Cogollo-Flórez, Alexander Correa-Espinal, Cristian Marquez-Rodríguez and Rosa Cacho-Figueroa. **P. 2874**

Pesquisa de alternativa de energia elétrica para la localidad de Fuerte Olimpo Chaco Paraguayo. Rina XXX, Germán González, Marcelo Marecos, Pedro Torres, Arturo Gonzalez, Gabriel Pereira and Victorio Oxilia. **P. 2882**

A Benders Decomposition Approach for an Integrated Bin Allocation and Vehicle Routing Problem in Municipal Waste Management. Arthur Mahéo, Diego Gabriel Rossit and Philip Kilby. **P. 2890**

Proposal of a Heuristic for Cluster Analysis with Application in Allocation of Anaerobic Co-Digesters for Biogas Production. Monique Simão, José Eduardo Pécora and Gustavo Loch. **P. 2905**

Optimal reverse supply chain design: the case of empty agrochemical containers. Glenda Yossen and Gabriela Henning. **P. 2916**

SIMPOSIO INDUSTRIAL

Prefacio. Simposio Industrial ICPR-Américas 2020. **P. 2932**

Índice de Satisfacción de Proveedores. Fernando Bono y Matías Sofía. **P. 2933**

Auditoría integral para una administración eficiente. Nicolás Bertoni. **P. 2942**

Mejora en la competitividad empresarial: acciones implementadas. Marcela Contreras, Luis Contreras, Emily Martinez. **P. 2946**

Confeccionando Futuro: curso técnico con función social. Gustavo Lari, Luis Contreras, Nerina Muñoz. **P. 2950**

Modificación en el sistema de retornabilidad de envases de Coca-Cola. Rodrigo Introcaso. **P. 2956**

Estudio del aumento de la capacidad de molinenda ensistemas de producción de alimentos balanceados. Jacqueline Claudia Lobos de Ponga, Agustina Di Battista, Sofia Bonifacino, Melisa Sequeira, Ivana Cotabarren, Juliana Piña. **P. 2960**

Programa motivacional en una pyme bahiense. Ariel Muzi. **P. 2964**

Sistema logístico integrado para la gestión operativa de carga y despacho de camiones. Augusto Ferraro, Joaquín Alencastre Cordi. **P. 2969**

Innovación en la industria petroquímica. Cristian Zurlo, Mateo Pilia, Xoana Alimenti. **P. 2973**

Índice de Calidad de Vida Laboral. Horacio Car-
dozo, Jesica Pereyra Rodríguez. **P. 2981**

**Adaptaciones a las nuevas demandas y tenden-
cias.** Gustavo Lari. **P. 2987**

**Herramienta de Gestión – Pool de Contene-
dores Vacíos para ordenes MPC.** Alencastre
Cordi Joaquín, Ferraro Augusto. **P. 2992**

**Desarrollo de un Caso de Uso de Industria 4.0
en una Planta de Producción de Aguas y Gaseo-
sa.** Agustín Carbone, Marisa Sánchez. **P. 2996**

**La pandemia como oportunidad para reinven-
tarse.** Ariel Rodríguez, Yamila Pérez. **P. 3006**

**Simulación de un proceso Inbound Freight de
Estados Unidos de América hacia las ciudades
de Saltillo y Toluca como herramienta para la
evaluación y mejora de los procesos en Facil
N. A. de México.** Luis Armando Peña González,
Juan Carlos Alonso Torres, Javier García Gutiér-
rez and Jenaro Nosedal Sánchez. **P. 3010**

**La Manufactura Aditiva como herramienta
clave en la modernización de los procesos de
fundición.** Pizzolito, Danilo. **P. 3024**

**Optimización de tiempos en Ordenes de Trans-
porte en empresa de servicios petroleros.**
Chaulet, Marcelo. **P. 3032**

SEMINARIO DE ENSAYO ESTUDIANTILES

Prefacio. Seminario de Ensayos Estudiantiles
ICPR-Américas 2020. **P. 3042**

**Economía Circular: El flujo de información en la
Cadena de Suministro.** María Luján Neri. **P. 3041**

Actitud renovable. Tomás Pereyra. **P. 3048**

Construcción sustentable y smart city. Carolina
Ailen Sepulveda. **P. 3053**

Simultaneous lot-sizing and scheduling with recovery options: problem formulation and analysis of the single-product case

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Abstract. We address an extension of the discrete lot-sizing and scheduling problem in which the demand of products can be also satisfied by remanufacturing used products returned to the origin. A mixed-integer linear programming formulation is provided for the problem, assuming dynamic demand and returns values, and time-invariant costs of setup and holding inventory. We then present a numerical experimentation carried out with the mathematical model for the case of a single product, in order to evaluate the efficiency in both costs and solving times compared to the traditional problem without returns. From the results obtained we conclude that the problem with recovery options can lead to economic benefits only under certain assumptions on the costs and amounts of returns. In addition, according to the runtimes obtained for large instances of the problem, it seems to be much more difficult to solve than its traditional version without returns.

Keywords: lot-sizing, scheduling, remanufacturing, mathematical programming, optimization

1 Introduction

The discrete lot-sizing and scheduling problem (DLSP) refers to the problem of simultaneously determining the lots and sequence of production for a set of products, in order to meet the demand requirements on time, minimizing the sum of production and inventory holding costs. Unlike other lot-sizing problems, in the DLSP only one item can be produced at each period and the production process runs at full capacity, i.e., small bucket periods and all-or-nothing production policy are assumed. Therefore, the quantity of production in a period established as a positive production period is determined based on a certain production speed

expressed in units per period. In addition, setup costs are only incurred when there is product changeover, i.e., configuration costs of the production line are only incurred at the beginning of the production process of a product.

A mixed-integer linear programming (MILP) and a heuristic solving approach for the DLSP in the case of a single machine is proposed in [3]. In [4] the DLSP with sequence-dependent setup costs is formulated and analyzed. Salomon et al. in [17] present a classification scheme and complexity results for the DLSP. In particular, they demonstrated that the DLSP with stationary costs, positive setup costs and single machine is NP-hard. However, they note that the DLSP for a single product can be efficiently solved as in [8] and [24]. Several extensions and solving approaches have been proposed in the literature for the DLSP, such as [23] for costs with non-speculative motives and [7] for start-up times and backlogging in the context of a tire curing scheduling problem. More recently, the DLSP with sequence-dependent changeover costs and time is addressed in [5]. Bi-objective formulations for the DLSP considering carbon emissions and renewable energy are presented in [10]. We refer the readers to [1] and [25] for recent surveys about the DLSP and extensions.

In recent years, the circular economy (CE) paradigm has emerged as an alternative to face the negative impact on the environment of the traditional linear model of producing, consuming and disposing [21]. As a recovery option, remanufacturing can be considered a critical component of the CE as it attempts to maintain the value of used products (also called cores or returns) and to reduce the use of raw material and energy [9], thus achieving a win-win-win situation for producers, consumers and environment. Remanufacturing is an industrial process in which it is warranted that a used product is returned to its original condition or even better. It often involves inspection, sorting, disassembling, cleaning, testing, reprocessing and reassembling tasks. Remanufacturable products include automotive parts, electric home appliances, personal computers, cellular phones, cameras, vending machines, among others [11]. In the field of production planning, we can find the seminal works of [15], [16] and [26] that extend the traditional economic lot-sizing problem (ELSP) in order to include returns flow and remanufacturing process. Teunter et al. [22] introduce the economic lot-sizing problem with remanufacturing (ELSR) with either joint or separate setup scheme. They provide an efficient algorithm for the joint case and extend the Silver-Meal heuristic for the problem. In [12] consider the ELSR with disposal of returns and in [18] suggest several improvements for the extended Silver-Meal heuristic. In [2], [19], [13] are suggested and evaluated different solving procedures for the ELSR based on metaheuristic approaches, and [14] considers the ELSR with recovery targets. We refer to [21] for a recent survey about production planning with recovery options.

In this paper, we extend the DLSP in order to include the returns flow, and assuming that demand can be also satisfied by remanufacturing used products. We refer to this problem extension as the discrete lot-sizing and scheduling problem with remanufacturing (DLSR). We provide a MILP formulation for the problem and present and analyze the results of a numerical experimentation

carried out in order to evaluate the efficiency in both costs and solving time of this hybrid production-remanufacturing system in the case of a single product. As far as we know, this DLSP extension has not been considered in the literature before. However, we note that there are some works that combine scheduling and remanufacturing, but for different problem assumptions [27], [6], [20].

The remainder of this paper is organized as follows. In Section 2 we present the description and the MILP formulation suggested for the problem under consideration. Section 3 provides the results and the analysis of the numerical experimentation carried out in order to evaluate the efficiency of the DLSR for the case of a single product. Finally, in Section 4 we present the conclusions and some possible directions for future research.

2 Problem description and formulation

The problem tackled in this paper can be stated as follows. We address a dynamic hybrid production-remanufacturing system with a single machine for processing $J > 0$ products under all-or-nothing production policy and over a finite planning horizon $T > 0$. Small-bucket periods are assumed. Therefore, only one product can be produced or remanufactured, but not both in the same period. The production and remanufacturing speeds for each product j , p_j and r_j respectively, are expressed as unit per period. Demand for a product j in a period t must be satisfied on time (backlogging is not allowed) from produced or remanufactured products generated in the same period (zero lead-time is assumed) or in a previous period and held in the inventory of serviceable products. Demand and returns values are assumed known in advance for each product and period over the planning horizon. Production and remanufacturing setup costs are incurred when there is product changeover. There are also linear costs for carrying on one unit of serviceable or used product from one period to the next one. Setup and inventory holding costs are assumed known and time-invariant. The objective is to determine the lots and sequence of products to be produced and remanufactured in order to satisfy the demand requirements on time, minimizing the sum of the costs involved.

Below we present the notation used for the problem from here and throughout the rest of the paper.

Sets and indices:

J : Number of products, with index $j \in \{1, \dots, J\}$.

T : Number of periods, with index $t \in \{0, 1, \dots, T\}$.

Parameters:

- D_{jt} : Demand of product j in period $t > 0$.
 R_{jt} : Returns of product j available in period $t > 0$.
 K_j^p : Production setup cost of product j .
 K_j^r : Remanufacturing setup cost of product j .
 h_j^s : Holding cost for serviceable product j per unit and per period.
 h_j^u : Holding cost for used product j per unit and per period.
 p_j : Production speed for product j (units per period).
 r_j : Remanufacturing speed for product j (units per period).

Variables:

- I_{jt}^s : Inventory of serviceable product j at the end of period t .
 I_{jt}^u : Inventory of used product j at the end of period t .
 y_{jt}^p : $y_{jt}^p = 1$ indicates that product j is produced in period t ;
 $y_{jt}^p = 0$, otherwise.
 y_{jt}^r : $y_{jt}^r = 1$ indicates that used product j is remanufactured in period t ;
 $y_{jt}^r = 0$, otherwise.
 z_{jt}^p : $z_{jt}^p = 1$ indicates a production setup for product j in period $t > 0$;
 $z_{jt}^p = 0$, otherwise.
 z_{jt}^r : $z_{jt}^r = 1$ indicates a remanufacturing setup for product j in period $t > 0$;
 $z_{jt}^r = 0$, otherwise.

Based on the notation of above, the DLSR can be formulated as the following MILP. We note that it can be considered an extension of that introduced in [8] and [24] for the DLSP.

$$\min \quad \sum_{j=1}^J \sum_{t=1}^T (K_j^p z_{jt}^p + K_j^r z_{jt}^r + h_j^s I_{jt}^s + h_j^u I_{jt}^u) \quad (1)$$

$$\text{s.t.} \quad I_{jt}^s = I_{j(t-1)}^s + p_j y_{jt}^p + r_j y_{jt}^r - D_{jt}, \quad \forall j, t > 0 \quad (2)$$

$$I_{jt}^u = I_{j(t-1)}^u + R_{jt} - r_j y_{jt}^r, \quad \forall j, t > 0 \quad (3)$$

$$\sum_{j=1}^J (y_{jt}^p + y_{jt}^r) \leq 1, \quad \forall t > 0 \quad (4)$$

$$z_{jt}^p = y_{jt}^p - y_{j(t-1)}^p, \quad \forall j, t > 0 \quad (5)$$

$$z_{jt}^r = y_{jt}^r - y_{j(t-1)}^r, \quad \forall j, t > 0 \quad (6)$$

$$I_{j0}^s = I_{j0}^u = y_{j0}^p = y_{j0}^r = 0, \quad \forall j \quad (7)$$

$$I_{jt}^s, I_{jt}^u \geq 0, \quad \forall j, t \quad (8)$$

$$y_{jt}^p, y_{jt}^r, z_{jt}^p, z_{jt}^r \in \{0, 1\}, \quad \forall j, t \quad (9)$$

The objective function (1) minimizes the sum of setup and inventory holding costs. Constraints (2) and (3) are the inventory balance equations for serviceable and used products, respectively. Constraints (4) establish that: i) only one product can be produced or remanufactured in certain period; ii) production and remanufacturing can not be carried out in the same period. Constraints (5) and (6) are for establishing the production and remanufacturing setup cost incurred when there is product changeover, respectively. The constraints (7) mean that the initial inventory level for all products is assumed zero and that the system is initially idle. Finally, (8) and (9) are the domain constraints for the decision variables.

3 Numerical experimentation

In this section we provide the results and the analysis of the numerical experiments carried out to evaluate the mathematical model suggested for the DLSR. Specifically, we are interested in compare the efficiency in both costs and solving time for the problem with and without returns, i.e, the DLSR and the DLSP. We note that the MILP of Section 2 in which the parameters, variables and specific constraints related to returns are removed, corresponds to the formulation of the DLSP.

To facilitate the understanding of the results and to make a more effective comparison, we consider for the experiments the case of a single product ($j = 1$).

3.1 Experiments design

The instances were generated based on the benchmark set introduced in [22] and [18] for the ELSR, also used in [2], [19], [13] and [14]. All them have a

planning horizon T of 22 periods (workdays of a month). Demand values D_{1t} were generated according to a normal distribution with mean 100 and 20% of coefficient variation. Returns R_{1t} were also generated using a normal distribution with means 50, 70 and 100, and 20% of coefficient variation. The setup cost of production K_1^p is set to 2000 and the setup cost of remanufacturing K_1^r can be 200, 500 and 2000. The unit cost for holding inventory of serviceable products h_1^s is set to 1 and for used products h_1^u can be 0.2, 0.5 and 0.8. Production speed p_1 is set to 200 units per period, and the remanufacturing speed r_1 can take values on 200, 300 and 400 units per period. Note that, as is to be expected in practice, it is assumed that remanufacturing costs are at most equal to production costs and that remanufacturing speed is at least equal to production speed. We generate 10 instances for each one of the 3^4 configurations, that is 810 instances in total. In addition, to evaluate the solving time, we generate one instance for each configuration, with planning horizons of 22, 44, 66, 88, 110 and 132 periods, that is $81 \times 6 = 486$ instances in total.

The model was coded in AMPL and solved for all the instances of above with CPLEX 12.9.0.0 with a time limit of 1800 seconds, on a PC with 8 CPUs Intel Core i7-6700 3.40GHz, 64-bit, 24GB of RAM and CentOS Linux 7.

3.2 Analysis of results for instances with $T = 22$

Next, we present and analyze the results obtained for the instances with a planning horizon of $T = 22$ periods. The values shown in Table 1 are the average cost, the standard deviation and maximum cost of the optimal solutions obtained with CPLEX for the DLSR and DLSP. We decided not to report the runtimes, since they were very low for both problems, less than half a second for all the 810 instances. In the first row of the table, labeled as “*All instances*”, we show the average cost considering all the instances, which is 12480.1 for the DLSR and 10828.9 for the DLSP. This represents around of 15% increase in the costs for the DLSR in average. However, we can note that in the cases of low-cost returns ($K_1^r = 200$ or $h_1^u = 0.2$), the costs are in average a little more favorable for the DLSR. The average costs of these cases are highlighted in the table (underlined and in bold). In fact, for each one of the 90 instances with $K_1^r = 200$ and $h_1^u = 0.2$, we want to remark that the cost of the DLSR optimal solutions is lower than the cost of the DLSP optimal solutions, even reaching differences of more than 35% in favor of the DLSR. We also note that the total number of instances for which the cost is favorable for the DLSR is 255, that is 30% of the total instances. On the other hand, we note that the maximum gap between the average costs of the DLSR and DLSP is for the cases of high-cost returns ($K_1^r = 2000$ and/or $h_1^u = 0.8$).

In the cases of variations on the average quantity of returns (R_{1t}), we note that they do not have a significant impact on the cost gaps. However, we note a favorable trend to the DLSR as the amount of returns increase, as it can be noted for the case of large returns ($R_{1t} = 100$). The opposite behaviour can be observed for the remanufacturing speed (three last rows of Table 1): as the remanufacturing speed increases, also do the average cost gap between DLSR and

DLSP. Therefore, it would be more economically convenient to consider similar speeds for production and remanufacturing, although in fact the remanufacturing speed could be higher, as it often requires less labor effort, materials, and energy.

In Table 1, the higher standard deviation and maximum values obtained for the DLSR compared to the DLSP, may be due to the fact that the variations are in the parameters related to the returns, which do not affect the DLSP. However, this appreciable dispersion in the costs of the DLSR optimal solutions observed for all the instances, would show that the variation in the parameter values has a significant impact on the efficient resolution of the problem.

Table 1. Summary of results for the 810 instances with $T = 22$ for DLSR and DLSP. The columns represent the average, standard deviation and maximum value of the optimal solutions obtained with CPLEX.

		<i>Average</i>		<i>Stand. desv.</i>		<i>Maximum</i>	
		DLSR	DLSP	DLSR	DLSP	DLSR	DLSP
<i>All instances</i>		12480.1	10828.9	2858.7	413.6	21086.2	12065.0
R_{1t}	50	12653.5	10837.5	2206.8	402.9	18098.0	12065.0
	70	12625.5	10841.8	2671.6	438.0	19351.6	11930.0
	100	12161.3	10807.3	3523.8	399.4	21086.2	12007.0
K_1^r	200	10447.5	10834.4	1890.4	407.0	14865.8	12065.0
	500	11553.2	10816.9	1712.9	413.3	15839.8	11868.0
	2000	15439.6	10835.3	2066.4	421.6	21086.2	12007.0
	0.2	10600.6	10804.5	2116.3	393.0	15177.6	11794.0
h_1^u	0.5	12582.6	10850.2	2483.1	442.9	17746.0	12065.0
	0.8	14257.1	10831.9	2684.7	403.4	21086.2	11930.0
	200	11519.7	10846.1	2672.3	419.6	17711.6	12065.0
r_1	300	12610.2	10819.1	2825.5	433.9	20403.2	12007.0
	400	13310.3	10821.5	2796.2	386.9	21086.2	11930.0

The cases in which the DLSR obtained lower costs than DLSP, that is, $K_1^r = 200$ and $h_1^u = 0.2$, are presented in more detail in Tables 2 and 3, respectively.

Table 2 shows the average cost of the optimal solutions for the DLSR and DLSP for the instances with $K_1^r = 200$. The rest of the parameters (R_{1t} , h_1^u and r_1) vary as described in Section 3.1. In column “Gap” we report the difference in percentage between the average costs of the optimal solutions determined as: $100 \times (DLSR_cost - DLSP_cost) / DLSP_cost$. From Table 2 we first note that the DLSR average costs are lower than DLSP in most cases (negative values in the Gap column). In terms of R_{1t} , it can be seen that as the value of returns increases, the cost of the DLSR optimal solutions decreases, reaching a percentage gap near to -14%. For the cases of h_1^u , we note that the sensitivity of the DLSR is significant with respect to this parameter, since the cost gaps vary from -19.3% ($h_1^u = 0.2$) to 11.3% ($h_1^u = 0.8$). Regarding the remanufacturing speed r_1 , the analysis is similar to the cases of h_1^u : the cost of the DLSR is very sensitive and increases as the value of r_1 increases, as we mentioned at the beginning of this subsection for the analysis of the results presented in Table 1. In addition,

Table 2. Comparison of the average costs of the DLSR and DLSP optimal solutions for the case $K_1^r = 200$.

		DLSR	DLSP	Gap
$K_1^r = 200$	R_{1t}	50	11217.9	10789.1 4.0%
		70	10778.4	10877.5 -0.9%
		100	9346.2	10836.6 -13.8%
	h_1^u	0.2	8736.0	10831.8 -19.3%
		0.5	10520.5	10816.1 -2.7%
		0.8	12086.0	10855.3 11.3%
	r_1	200	9415.7	10881.8 -13.5%
		300	10527.7	10810.3 -2.6%
		400	11399.1	10811.1 5.4%

we observe that the costs are significantly favorable for the DLSR in the case in which the production and remanufacturing speed are the same ($p_1 = r_1 = 200$).

Table 3. Comparison of the average costs of the DLSR and DLSP optimal solutions for the case $h_1^u = 0.2$.

		DLSR	DLSP	Gap
$h_1^u = 0.2$	R_{1t}	50	10938.7	10812.1 1.2%
		70	10636.5	10856.8 -2.0%
		100	10226.5	10744.7 -4.8%
	K_1^r	200	8736.0	10831.8 -19.3%
		500	9862.4	10808.2 -8.8%
		2000	13203.3	10773.7 22.6%
	r_1	200	9881.1	10833.5 -8.8%
		300	10740.5	10801.3 -0.6%
		400	11180.1	10778.9 3.7%

Table 3 shows the results for the instances with $h_1^u = 0.2$. The meaning of the columns is the same as in Table 2. From Table 3 we can note that there are more instances in which the costs of the DLSR is lower than the costs of the DLSP (negative values in column “Gap”). The effect observed for the returns cases R_{1t} is similar to that seen in Table 2, but less marked: as returns amounts increase, the cost of the DLSR decreases. A high sensitivity for the costs of the DLSR optimal solutions is observed against different values of K_1^r , with a percentage gap from -19.3% for $K_1^r = 200$ to 22.6% for $K_1^r = 2000$. For the cases of the remanufacturing speed (r_1), the results are also similar for that observed in Table 2, but, once again, not so marked.

3.3 Analysis of results for large instances

We present in this subsection the results of the experiments carried out to evaluate the computational effort required to solve the problems DLSR and DLSP.

In Table 4 we present the runtimes in seconds for each problem, along with the number of times that the time limit of 1800 seconds, established to CPLEX, is attained. In Figure 1 we show the CPU times required by CPLEX for solving the problems for the different values of T under consideration, represented on a logarithmic scale. As it can be seen in Table 4 and Figure 1, DLSR is considerably more computationally expensive than DLSP. While the CPU times for the DLSP are around 1 second (even for the larger case of $T = 132$), in the case of the DLSR, they grow suddenly (more than 500 seconds for $T = 132$). This is evidenced by the number of times that the time limit of execution is reached by CPLEX for the DLSR, which begins to increase in larger instances. On the other hand, for the DLSP the time limit is never attained.

Table 4. Average runtimes (in seconds) and number of times that the execution time limit is reached by CPLEX to solve the problems DLSR and DLSP for the different values of T considered.

T	DLSR		DLSP	
	Runtime	#Tim.lim.	Runtime	#Tim.lim.
22	0.07	0	0.006	0
44	0.53	0	0.10	0
66	9.02	0	0.26	0
88	134.03	4	0.82	0
110	362.44	13	1.11	0
132	513.67	19	1.34	0

Finally, we note that the cost gaps for the large instances show, on average, the same behaviour as that observed for the 810 instances with $T = 22$ periods, that is, around a 15% increase for the DLSR compared to the DLSP.

4 Conclusions

In this paper we have tackled an extension of the discrete lot-sizing and scheduling problem in which the demand requirements of products can be also satisfied by remanufacturing used products returned to the origin. We refer to this problem as the discrete lot-sizing and scheduling problem with remanufacturing (DLSR). Remanufacturing can be considered as a key element of the Circular Economy, a paradigm that has emerged to counteract the negative effect on the environment of the traditional linear production of produce, use and dispose.

We provide a MILP formulation for the problem and analyze the results of a numerical experimentation carried out for the case of a single product, with the aim to compare the efficiency in both costs and solving time of the DLSR against the DLSP (the traditional problem without returns). From the numerical experiments conducted, we conclude that the problem extension with recovery options can offer economic benefits in the case of low-cost returns and, to a lesser extent, for those cases in which the number of returns is relatively high compared

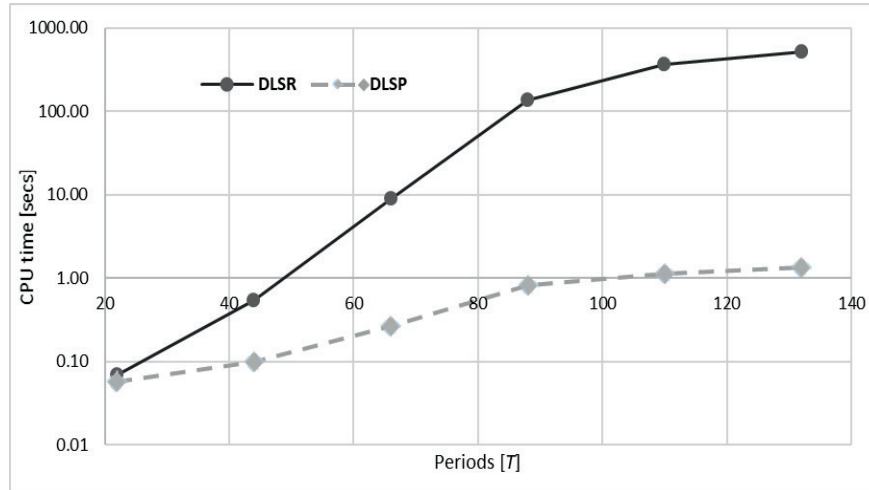


Fig. 1. CPU times in average required by CPLEX to solve the problems DLSR and DLSP for the different values of T . The CPU time is expressed in logarithmic scale in seconds.

to the demand requirements. In addition, we note that similar production and remanufacturing speeds appear to be a more favorable configuration, even in those cases with large returns. In terms of solving times, we show that the DLSR is much harder to solve than the DLSP, in particular, as the size of the instances increases. Thus, we conjecture that the DLSR belongs to the complexity class of NP-hard problems.

Taking into account the results of the numerical experimentation summarized above, future research on DLSR should involve the development of efficient and effective solving procedures for the problem, possibly extending those suggested for the DLSP or ELSR. Another interesting topic to address is the analysis of the order of complexity of the problem. This analysis should involve not only the general case, but also particular cases such as the case of a single product as in [24] for the DLSP, or the case of sufficient returns at the first period as in [15] and [16] for ELSR. It would be also interesting to study the DLSR with more than one machine or processing line. In particular, the case in which production and remanufacturing are allowed in the same period. Considering the environmental side of the problem, it would be interesting to investigate the returns usage rate in the optimal or high quality solutions. Also including more realistic assumptions, such as the non-uniform condition of the returns (heterogeneous quality), may be an interesting extension to consider for the problem tackled here.

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